

Toward robust and safe closed-loop control of anesthesia

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a place of mind

THE UNIVERSITY OF BRITISH COLUMBIA



Outline

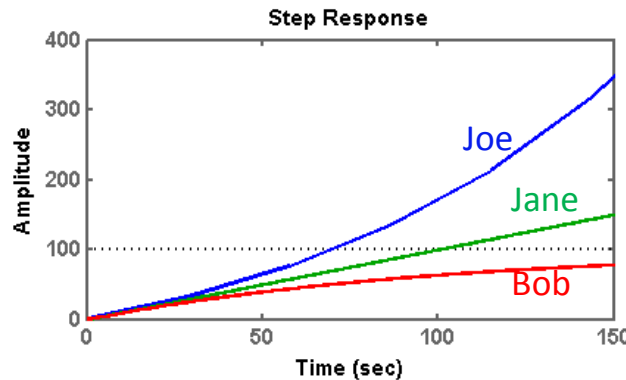
Challenges imposed by interpatient variability

- Robustness to variability through **design**
- Judging the severity of variability
- Robust control
 - Modeling and design
- Development of robust control system for propofol anesthesia in ECEM group
- Clinical evaluation of robust PID control



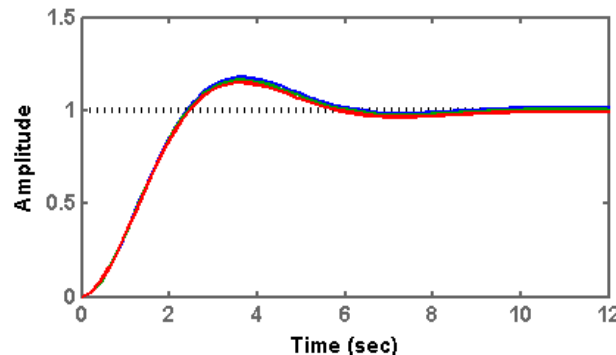
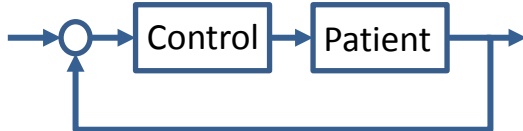
Judging the severity of variability

Open-loop



Impact of variability on closed-loop behaviour difficult to judge from open-loop time responses

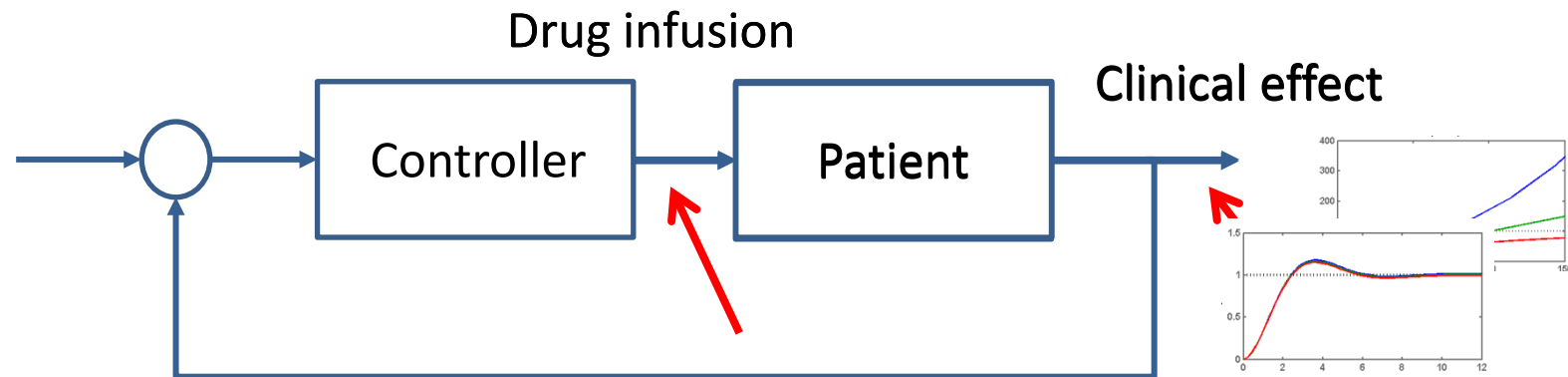
Closed-loop



Significant changes in open-loop responses may have little effect on closed-loop response

Judging the severity of variability

Feedback: reduce variability at the output



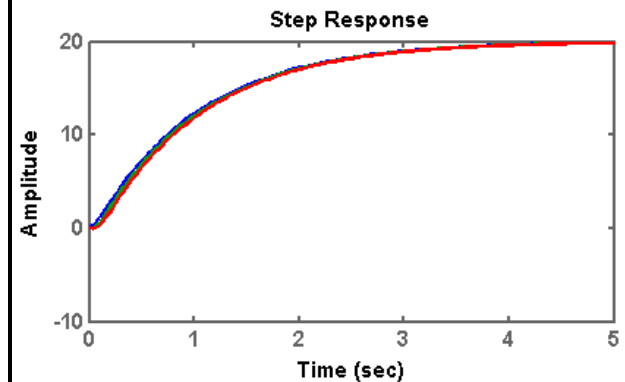
- Move variability to the input

Judging the severity of variability

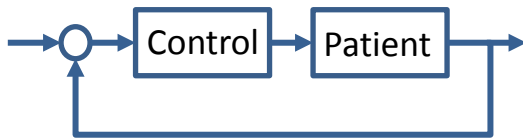
Open-loop



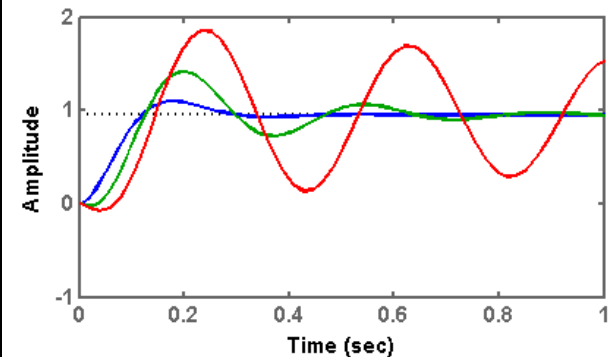
Impact of variability on closed-loop behaviour difficult to judge from open-loop time responses



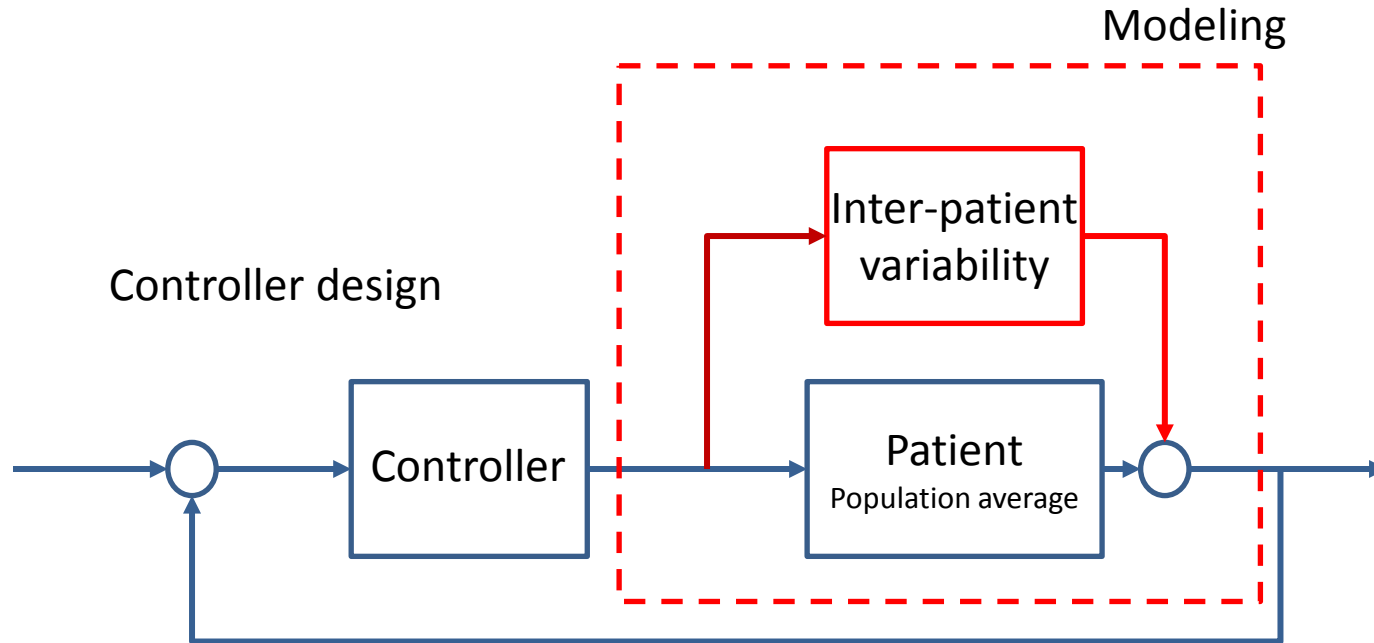
Closed-loop



Small changes in open-loop responses may have significant effect on closed-loop response



Robust control



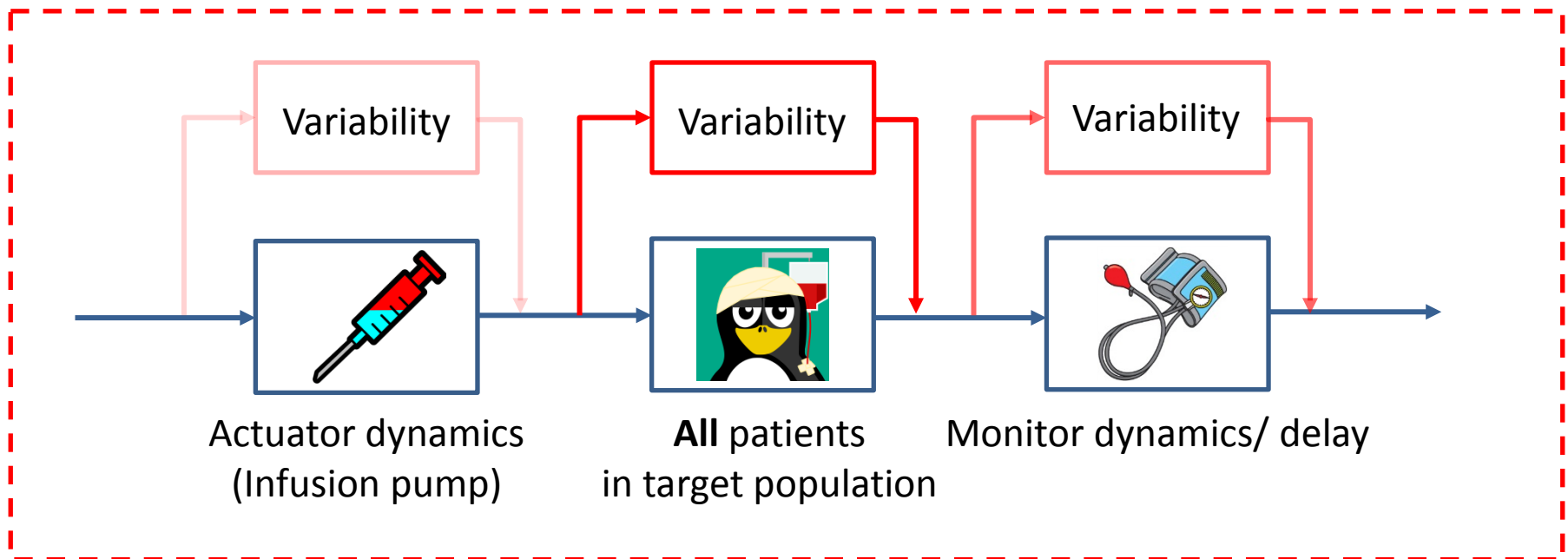
Robust control theory:

- Design to ***guarantee*** stability and minimal performance despite the ***expected uncertainty***

Modeling for robust control

Expected uncertainty, more than just patient

- Model system dynamics **and uncertainty**



Robust PID control of propofol anesthesia

Trade-off between uncertainty and performance

Our approach: **Simple design**

PID = proportional-integral derivative

- 90% of process control and mechatronics applications
- Can simple robust PID design achieve requirements given inter-patient variability?

Rigorous design process:

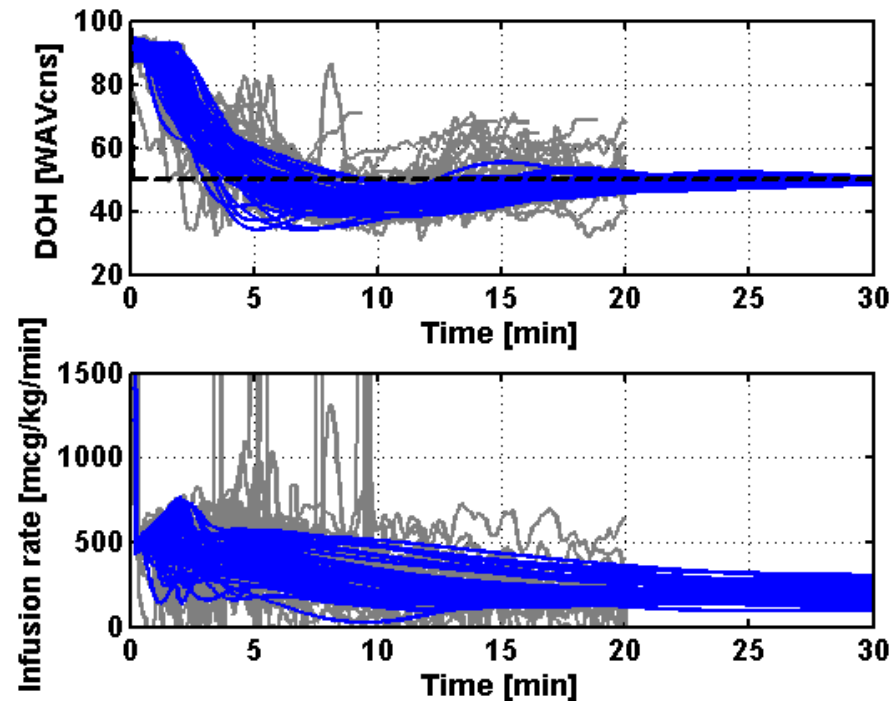
- Modeling, model validation
- Robust controller design



Robust PID control of propofol anesthesia

Modeling

- Multi-model approach
 - Identification from clinical data: expected uncertainty and outliers
 - Validation
- Set of models** of individual patient responses



Robust PID control of propofol anesthesia

Controller design

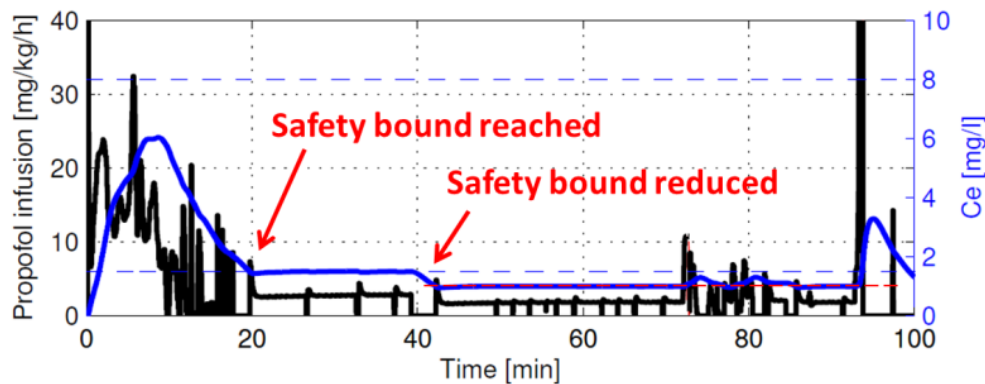
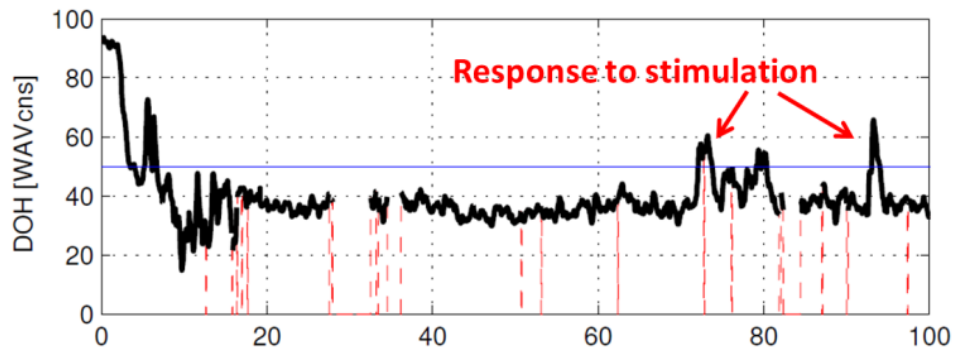
PID design model based? Yes, multi-model design

- Robustness by loop shaping for ***all models***
 - Sufficient margins for all models
- Robust performance in both frequency and time domain
 - Simulations studies including all models: Induction of anesthesia, response to disturbances
 - Performance adequate for clinical use?
- Simple robust PID design achieves requirements

Robust PID control of propofol anesthesia

Safety system and testing

- Safety system (fallback, constraints)



- **Safety preserving control**, techniques developed for aerospace, extending to uncertainty
- **Simulation studies** in presence of faults (scenarios)

Robust PID control of propofol anesthesia

System design and testing

- Risk analysis, risk mitigation
- Software, hardware, user interface, usability
- System testing (software and hardware)
 - Automated simulation tests
 - Manual testing
 - Faults, clinical scenarios
 - Hardware failure etc.
 - Hardware in the loop



Robust PID control of propofol anesthesia

Clinical evaluation

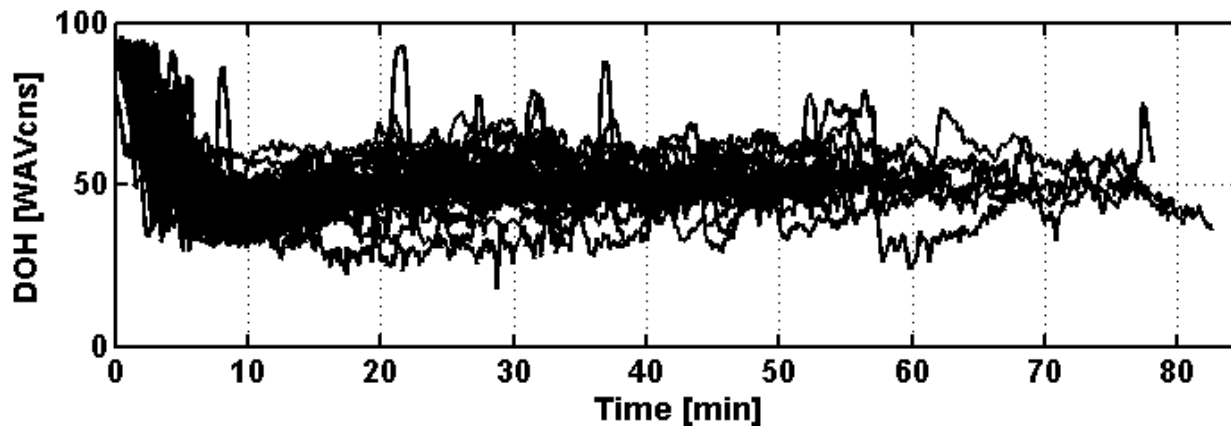
- Health Canada approved for clinical investigation, Research Ethics Board approval
- CL control of induction and maintenance of propofol anesthesia in children
 - Gastrointestinal endoscopy: 102 cases
- CL control of induction and maintenance of propofol/remifentanyl anesthesia in adults
 - Elective surgery: ongoing (130 cases)

Closed-loop propofol anesthesia in children

Gastrointestinal endoscopy: 102 cases, 53 F, 12.5 y (6–17), 48 kg (19–75), 156 cm (112–185), ASA I-II

Spontaneous breathing

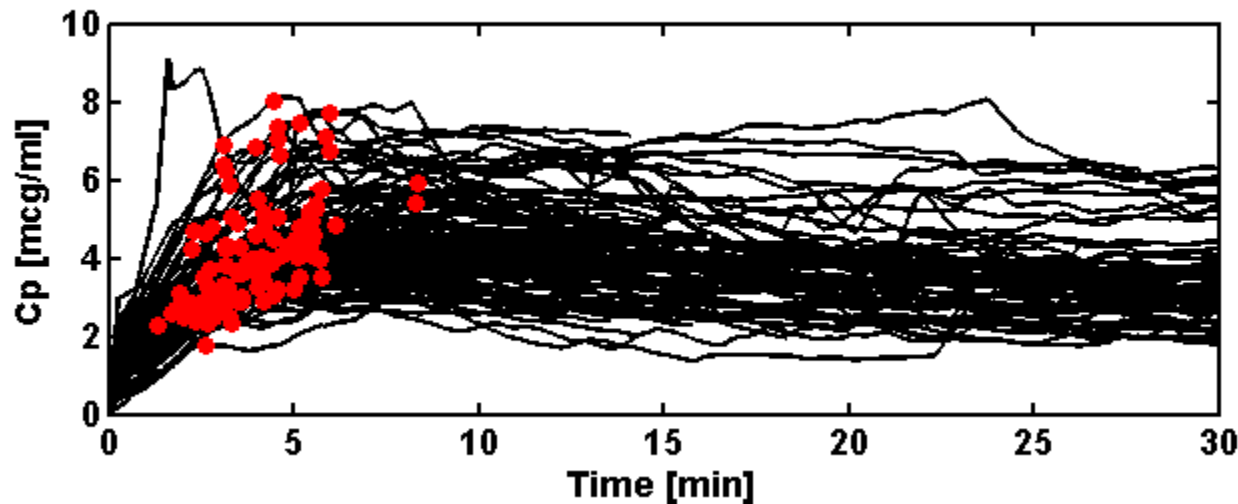
- Maintained without manual intervention in 91/102 (89%)
- Airway maneuver (n= 9) , setpoint increase (n=2), remifentanyl decrease (n= 1)



Closed-loop propofol anesthesia in children

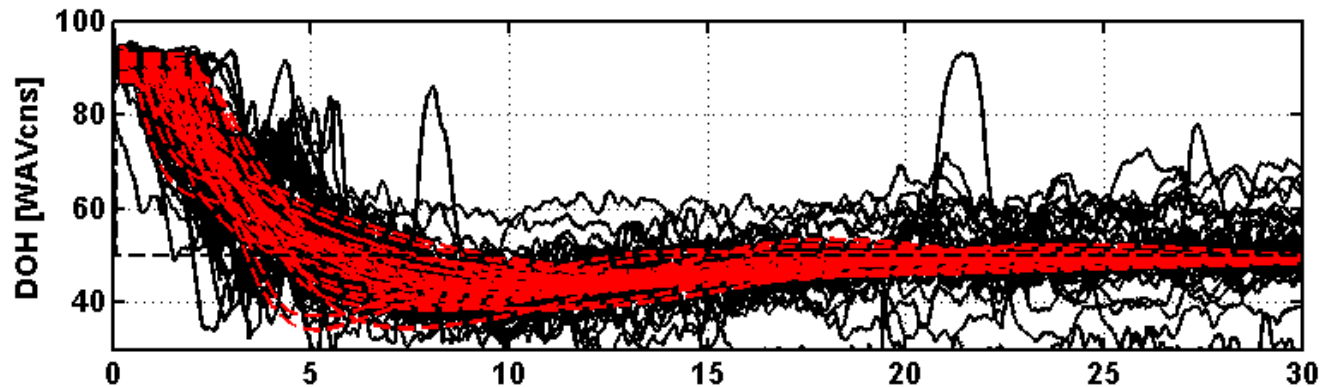
Variability moved to input (drug infusion)

- Reflected in predicted plasma concentration
- Red dots = induction complete = target achieved



Evaluation of robust controller design process

- Predicted response in controller design stage (28 models)
- Clinical responses (71 cases)



- Expected uncertainty described by set of models is realistic
- Predicted response and robustness margins are realistic
- Multi-model design performs as expected
- Robust PID control of propofol infusion is feasible



Thank you for your attention

N. West et al. *Robust closed-loop control of induction and maintenance of propofol anesthesia in children*, Pediatric Anesthesia. 2013 Aug;23(8):712-9

K. van Heusden et al. *Quantification of the variability in response to propofol administration in children*, IEEE Transactions on Biomedical Engineering. 2013 Sep;60(9):2521-9

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